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Successful Partnership Between Brookhaven National Laboratory and Northrop Grumman Corp. for Construction of RHIC Superconducting Magnets+

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Abstract-- This paper summarizes the structure and execution (or 'history') of the contract between the RHIC Project at Brookhaven National Laboratory and the Northrop Grumman Corporation for construction of the 8cm aperture superconducting dipoles needed for RHIC. A total of 373 dipoles were built for a contracted price of $43 M. Two smaller contracts for RHIC superconducting magnets are also discussed.

Index Terms—Northrop Grumman, RHIC, Superconducting Magnets, Industrial Contracts

I. Introduction

It is a matter of record that the 8cm dipole superconducting magnets manufactured by the Northrop Grumman Corp. (NGC) for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) met the RHIC performance specifications with considerable margin [1]. This was the end result of meticulous planning and execution to forge a successful partnership between a national laboratory and an industrial entity. This paper attempts to record the key elements that made that partnership successful.

II. Early Planning

As the planning for the manufacture of the RHIC superconducting magnets began, BNL had to make a basic decision whether to manufacture all of the magnets itself or to go to an industrial company for magnet manufacture. The following facts formed the basis for the decision to go to industry for a portion of the magnets:

1. The total requirements for RHIC magnets at that time (October 1990) were 1656 magnet elements (not including spares) to be produced within a period of four years. (By 1992, this number had grown to 1740.)

2. BNL, as a national research and development laboratory, did not have the manpower, facilities and equipment to produce the quantities of magnets required within the time limits imposed; therefore, some production had to be given to industry.

Industry was best at mass production of identical products. Therefore, identical or nearly identical magnets with large production quantities (i.e., 8cm dipoles, 8cm quadrupoles, 8cm sextupoles, and 8cm trim quadrupoles) were selected for industrial production. At a contracted value of $43M, the largest contract, by far, was the 8cm dipole. Therefore, an acquisition strategy for industrial production was developed for the dipoles and adjusted as necessary for the other magnet types depending on risk and contract value.

III. The Partnership Structure

With early planning complete, it was necessary to determine the structure under which industrial production would occur. First and foremost, it was recognized that BNL had to develop a true partnership with the companies that would be selected for industrial production. BNL had a long history of designing and manufacturing successful superconducting magnets for accelerator use. Even though U.S. industry had the mass production experience that BNL did not have, with few exceptions it did not have superconducting magnet experience. Therefore, BNL had a responsibility to provide a proven design, transfer its knowledge and experience to industry, and be intimately involved throughout production to assist in identifying and resolving problems as they occurred. This had to be accomplished in an environment wherein both parties realized that they were committed to a common goal and must proceed as partners to accomplish that goal.

A partnership requires a clearly defined division of responsibilities which must be determined before deciding upon the formal contract structure. For the magnets to be produced by industry, the responsibilities were divided as follows:

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1. BNL retained design responsibility for the magnets. This meant that the contract with an industrial partner would be "build to print" wherein the contractor was responsible for building magnets to match BNL-supplied drawings, but was not responsible for actual magnet performance. This approach was possible because BNL, by building and testing model and full size magnets before completing the "final" design given to industry, had already proven that magnets built to the design would perform properly. Also, though not directly responsible for magnet performance, NGC had to demonstrate conformance to "product definition specifications" which included process parameter requirements and dimensions from the drawings and specifications which were explicitly listed in the contract. These specifications were monitored and reported on throughout the contract [2].

2. Certain critical materials and components were supplied by BNL to NGC. For example, superconducting cable and quench protection diodes were purchased and pre-qualified by BNL before being supplied to NGC. Also, magnetic measurement equipment, and associated power supplies and instrumentation, were designed and built by BNL and supplied to NGC. It was felt that BNL should retain the primary responsibility for these and other critical elements of the program, instead of requiring an inexperienced vendor to do so.

3. It was recognized that the industrial partner would have significant knowledge and expertise in the area of establishing a production line for cost efficient mass production. Therefore, the design responsibility for the tooling required to produce the magnets was given to the industrial partner. However, because of its extensive experience in superconducting magnet construction and the fact that manufacturing tools play an important part in magnet performance, BNL retained its right to review and approve all tooling designs. To ensure the continued integrity of the production tooling, the contractor was restricted from making changes to tools without BNL's prior review and approval.

4. For the same reasons as for tooling, manufacturing and assembly methods and procedures became the responsibility of the industrial contractor. The same restrictions as for tooling were applied.

5. To give the partnership the best possible chance of success, BNL had a responsibility to transfer as much of its experience and knowledge to the industrial partner as possible. The method chosen to accomplish this was to implement a technology transfer program with the selected contractor (NGC) upon contract award. NGC design and production personnel attended a comprehensive magnet design and assembly seminar, hosted by their BNL counterparts. They then observed BNL technicians assemble a prototype magnet, and did all but a few critical assembly operations on a second prototype magnet. Frequent meetings were held with all concerned to address any questions or confusion that might arise. During these prototype builds, NGC tooling designers were taught the critical design considerations that went into each of BNL's tools. Finally, BNL engineers and technicians were sent to NGC's facility to review procedures, help debug tools, and observe their technicians during construction of the first two production magnets. (For a more extensive description of the technology transfer, see [3].)

6. Another BNL responsibility was to assist the industrial partner in identifying and resolving problems as they occurred during production. This was accomplished by assigning a BNL representative to reside full time at the production site and by holding regularly scheduled (monthly) progress meetings. These meetings were attended by participants from both BNL and NGC with clearly defined areas of responsibility (i.e., business, technical, quality, contract, etc.). During meetings, any problems not fully resolved became the action item of that/those individuals who were involved in the discussion of the problem and held that specific responsibility. Any problems which arose between meetings were quickly referred to the appropriate responsible persons by the on site BNL representative. As it turned out, the close proximity of NGC's production facility to BNL (about 40 miles) was extremely beneficial to the ultimate success of the partnership. When a problem occurred, the appropriate BNL engineer or technician could be at the facility within an hour to assist in problem resolution and minimize cost and schedule impact. An account of some of the specific problems encountered and resolved can be found in references [4,5].

IV. Contract Structure and Type

After determining the partnership structure that would be put in place, the next action was to determine the type of contract structure that would be most conducive to making the partnership work.

A three phase structure within a single contract for each magnet family was decided upon. Phase 1 encompassed technology transfer, tooling design and manufacture, and a small amount of early production to prove out the tooling design and manufacturing/assembly methods and procedures. Phase 2 was full production of the main magnets, while Phase 3 was production, at the same rate in Phase 2, of magnets that varied slightly from the main magnet design and had a much lower production quantity. The purpose of a single contract was to, as much as possible, establish prices while the benefits of competition still existed.

Three basic contract types were considered: Cost Plus Fixed Fee (CPFF) (highest risk to the buyer), Fixed Price Incentive Firm (FPIF) (risk sharing between buyer and seller), and Firm Fixed Price (FFP) (highest risk to the seller). CPFF recognizes all costs incurred plus a fixed dollar amount for a fee. FPIF begins with a Target Cost and a Target Profit which make up a Target Price. The actual price paid is determined by a cost sharing arrangement wherein the Target Profit is adjusted in accordance with a cost sharing ratio, upward or downward, depending on whether actual costs are lower or higher than the Target Cost. Lower costs result in a lower price and higher profit; higher costs result in a higher price and lower profit. FPIF contracts also have a Ceiling Price which puts an upper limit on the buyer's cost exposure. FFP is a fixed price that does not change no matter what the actual costs turn out to be.

These three contract types were mixed and matched by contract and by phase based on an assessment of cost risk. As risk increased, the contract type that offered more flexibility in final price was chosen.

The dipole contract was the largest in value and was certainly the most important magnet element contributing to the ultimate success of RHIC. The unknowns associated with technology transfer, tooling design, tooling manufacture, and assembly of the first few magnets made Phase 1 a high risk work scope. For Phase 2, labor costs were readily predictable, but material costs represented a significant risk. Phase 3 was essentially the same as Phase 2 with the added risk of tooling changeover. Therefore, for the dipole contract, Phase 1 was CPFF and Phases 2 and 3 were FPIF.

For the quadrupole contract (estimated at a value of $5M), Phase 1 was not considered as much of a risk as the dipole, but Phases 2 and 3 were about the same as the dipole. Therefore, the entire contract was FPIF.

For the contract which contained both sextupoles and trim quadrupoles (estimated at a value of $2.5M), all risks were very low. Therefore, the entire contract was FFP.

V. Change Control

BNL and NGC realized both the need to have a mechanism for magnet design changes and the requirement to control the change process carefully. Although these were "build to print" contracts as previously mentioned, inevitably once the contracts began, discussions ensued between NGC and BNL, with input at times from NGC's subcontractors, over various improvements, corrections, and cost-saving measures. These potential changes were implemented only after the following were completed. First, an initial technical review was conducted at BNL, and, if acceptable, the change was formalized in a written Engineering Change Request (ECR). The ECR was then submitted to NGC for review. At NGC, all affected factions (Procurement, Tooling, Production, etc.) provided input as to any impact to cost and/or schedule. These inputs were formulated into an Impact Change Proposal (ICP) for each ECR. The ICP added overheads, etc., to the costs submitted to create a contract price for each requested change. The ICP was then reviewed at BNL and, if acceptable, the ECR was approved and became an Engineering Change Notice (ECN). The ECN was then released to NGC along with a contract modification, increasing or decreasing contract price as appropriate. In this way, changes were incorporated into the contract only when needed and agreed upon by both parties, and with cost and schedule inputs known and agreed upon in advance. This served as a strong tool to contain both the changes and the costs associated with the changes.

In some cases, though, changes were acknowledged to be necessary by both BNL and NGC, and schedule prohibited the aforementioned process to occur. In those limited instances, changes were approved and incorporated before the ICP was submitted. Even on these occasions, however, an attempt was made to control costs through meetings between BNL and NGC where the proposed costs of the ICP's were justified and/or negotiated. It should be pointed out that during the course of the contract, the additional price of all ECN's added less than $500K to the contract, including proposal costs, negotiated from a proposed price increase totaling $3M.

Separate from this activity were certain changes which were planned from the start of the contract. Specifically, when the dipole contract was signed, BNL reserved the right to make two specific design changes for improved magnetic performance. The first was a wedge and coil shim change prior to the start of unit #1. The second was a coil shim change only, prior to the start of unit #31. These changes, although not incorporated exactly as written, were made possible because they were identified at a detailed level in the contract, and included by NGC in the initial quoted price of the contract.

VI. Actual Performance

A. Production

The decision to retain magnet design responsibility at BNL, combined with real-time monitoring by BNL of magnetic field and construction data, was crucial to maintaining magnet performance. The very first magnet off the production line was of sufficient quality to be used in the RHIC accelerator, and 371 of 373 dipole magnets continued that excellent quality; the performance of the NGC production magnets exceeded that of the BNL-built prototypes which preceded them. Performance was good enough that BNL was able to reduce cold quench testing to an average of 20% sampling of the total quantity built, saving resources and money. (A more detailed description of magnet performance is given elsewhere [6].) Furthermore, the last magnet was delivered within three months of the original schedule date, set over three years earlier. The two magnets that were not accepted as ring magnets were built with construction flaws that were detected by BNL by analysis of data from the magnetic measurements, before the magnets were shipped from NGC.

Information obtained from RHIC operation makes possible a better assessment of the magnet performance than does the acceptance testing data, since only 20% of the arc dipoles were tested at cryogenic temperatures before installation. Much information is available from the RHIC commissioning during the summer of 1999. During this period, both rings of the collider stored injected beam. RF capture and acceleration were demonstrated in one ring. With no beam present, the arc dipoles and quadrupoles were ramped without quenching to 2.0 kA, 40% of the maximum operating current. No electrical problems were found in the magnets. There was only one leak in the magnet helium containment system, and none in the magnet vacuum system. The next commissioning period is scheduled to begin at the end of 1999.

B. Contract

The partnership and contract structures meshed well. For the dipole contract, the flexibility offered by the pricing structure allowed decisions to be made and actions to be taken without undue concern on the part of NGC regarding its profit position. As it turned out, the length and scope of technology transfer in Phase 1 was greatly underestimated by both BNL and NGC (lasting 8 months beyond schedule (17-25 months) and overrunning target cost by $13M ($12M-$25M). Had Phase 1 not been CPFF, the partnership would have failed due to one of several possible scenarios: NGC defaulting on the contract due to unreimbursed cost overruns, poor technical decisions made based on schedule or cost pressures, etc.

An added benefit was that the cost sharing aspects of the CPFF and FPIF pricing structures caused BNL to be more receptive to cost savings ideas presented by NGC. Tolerances, material specifications, magnet assembly design, tooling requirements, methods, and procedures were all subjected to cost savings reviews. Each cost savings suggestion received serious consideration from BNL because it would share in the savings.

Earlier it was stated that the labor costs of magnet manufacture were readily predictable. Figure 1 shows NGC's estimated hours per magnet as compared to actual hours. The first 30 magnets of Phase 1 underran the estimate by 18%. The 268 Phase 2 magnets underran by 8%. The unusually large underrun of Phase 1 manufacturing labor is directly attributable to the technology transfer program wherein NGC achieved much of the learning that normally would occur during the first few magnets prior to producing its first magnet.

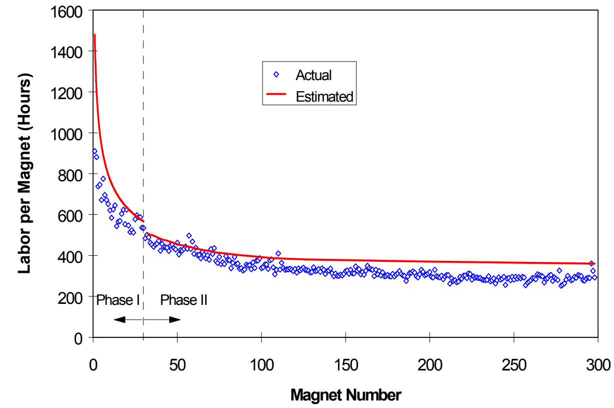

Fig. 1. Labor hours to build a magnet at NGC. The production magnets discussed here are those from Phase II.

Phase 2 actuals exhibited a learning curve that was better than estimated. The actual learning slope achieved was 85% [for every doubling of magnet production sequence number, (i.e., magnet number "2n") the number of hours required to produce the magnet is reduced to 85% of the hours it took to produce the doubled magnet sequence number, (i.e., magnet number "n") as compared to NGC's expected learning slope of 90%. Part of this "unexpected" improvement was due to an extensive labor hour reduction program implemented by NGC wherein the production line personnel were encouraged to find better ways to accomplish their jobs. For example, on a beam tube bumper installation tool, many bolts were replaced by toggle clamps to speed assembly and disassembly. BNL did its part by developing and testing new tools to ease the workload in heavy labor intensive areas.

Unfortunately, although production and material costs were well controlled, they represented only ~46% (8% labor, 38% material) of the total contract cost (see figure 2).

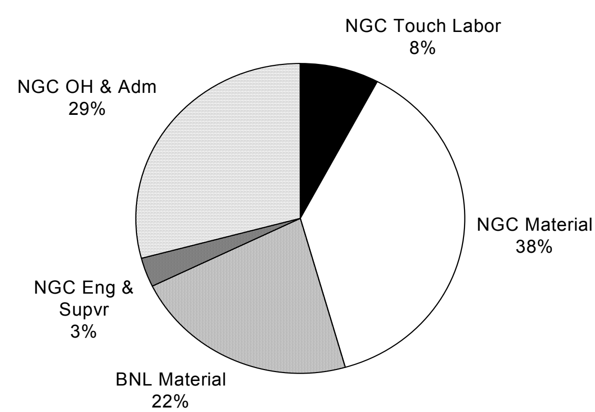

Fig. 2. Distribution of total costs for the production dipoles built by NGC.

Additional information about magnet costs is available in reference [7]. By contrast, overhead rates increased unchecked throughout the contract, as other NGC business centers scaled back activities and size dramatically, and a greater percentage of administrative costs were borne by the remaining groups. The result was that by contract end, increases in overhead rates had added $3M to the total cost of the contract. This issue should be addressed at the start of any future collaboration, to avoid the potential for this type of cost overrun.

VII. Program Management

Initially, the partnership worked well in spite of some very spirited disagreements which are to be expected when two groups with different backgrounds work together on a project. However, about two and a half years into the program, the original Program Manager assigned by NGC to the BNL contract departed from the partnership culture. Without conferring with BNL, he began implementing unauthorized changes to magnet tooling and assembly methods which could have seriously jeopardized the quality and performance of the magnets. At that point, BNL requested that NGC management remove the Program Manager, and they did so. The succeeding Program Manager, having worked well with BNL as the Lead Engineer for the contract, re-established the partnership culture and the contract was completed without further incident.

As a result of the effort to reduce the final bid price on the contract, the Quality Assurance effort was severely under-budgeted at the start of the contract. The QA Manager, short on staff, was then regularly slow to respond to problems throughout most of the contract. In particular, the original NGC philosophy (which was a part of the justification for reduced budgeting) whereby all subcontractors would be self-policing (and perform and attest to all their own inspections, etc.) did not work as planned, and the interaction with subcontractors drew needed resources away from in-house activities. As a result, repeated BNL intervention was necessary both on-site at NGC and also at subcontractor locations. Ultimately, the QA Manager was replaced some time after the new Program Manager assumed his duties, and more budget and resources were devoted to Quality Assurance.

VIII. Summary

As evidenced by the high quality and high performance of the delivered magnets, the partnership worked well. How well is probably best reflected in a remark made by the NGC Division General Manager responsible for the RHIC dipole magnets: "When I attended meetings intended to solve difficult and potentially contentious problems, I could not tell who were the NGC people and who were the BNL people. It was obvious that all were committed to the common goal of producing high performance, high quality magnets at the lowest possible cost on the best possible schedule." Like most working partnerships, however, there were of course problems, and inevitably disagreements over the proper solutions to those problems. What was essential to making the partnership work was a willingness from both parties to work tirelessly to solve all problems as they arose, in the most efficient manner possible, from the start of the contract to the finish. BNL, in particular, remained far more active and responsive than might be expected in traditional customer-supplier relationships.

That's what a partnership is all about.

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